Enabling dynamic all optical IP off-loading at Tb/s rates in large Metro Networks

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Abstract: Simulation experiments prove the suitability of VCSEL-based S-BVTs to enable IP off-loading in large MAN topologies. Multi-Tb/s capacity is demonstrated in a real MAN for all primary and secondary multi-level direct paths. © 2021 The Author(s)

1. Introduction

Annual traffic growth rates between 25% and 40% in the Metro segment are expected for the next years, as a consequence of the emergence of new services related with the arrival of 5G, the Internet of Things, Connected Industry 4.0 and the Cloud paradigm, among others. To cope with such massive traffic demand, both vendors and research community are looking for scalable cost-effective solutions. Particularly, [1] presented a system architecture based on the emerging photonic technology of vertical cavity surface emitting laser (VCSEL) at long wavelength as a novel, low-cost and power-efficient solution to operate in metro scenarios. Specifically, VCSEL technology and photonic integrated circuits (PICs) are combined to attain a programmable (SDN-enabled), modular and scalable sliceable bandwidth variable transceiver (S-BVT) featuring multiple flows to support Tb/s connections.

The S-BVTs proposed to be adopted are based on integrated VCSELs and coherent reception, according to the technologies developed within the context of the EU H2020 PASSION project. The VCSEL technology cost-effectively allows high modulation bandwidth (above 18 GHz) and C-band operation; while coherent reception ensures higher robustness against chromatic dispersion with respect to direct detection, thus, enhanced achievable longer reach to cover the targeted large MAN paths. This enables to support up to 50 Gb/s per flow with directly modulated (DM) VCSEL adopting multicarrier modulation (DMT or OFDM) [1]. Multiple flows (up to $m = 40$) can be activated/aggregated within a single integrated S-BVT module and, thanks to the modular approach, an easy upgrade to higher capacity can be enabled either exploiting the C-band (up to 8 Tb/s) or the spatial dimension (above 100 Tb/s) [1].

In general, MANs are arranged in a hierarchical aggregation/distribution structure, since most traffic (above 90%) goes from edge nodes to metro-core nodes (Internet, CDNs) and vice versa. Typically, a router of Hierarchical Level (HL) $n, n = 2, 3, 4, 5$ is logically connected (using an all-optical channel) to two routers at the immediately above hierarchical level $n - 1$. At the physical layer, however, this logical connection requires the traversal of a number of intermediate ROADMs before reaching router HL($n - 1$) making the skipping of IP hops challenging [2]. Furthermore, the role of IP is aggregating traffic, a complex operation at the optical layer.

In this work, we propose to take advantage of the sliceability property of S-BVTs to replace IP aggregation at the transit level HL3 and hence interconnect all optically HL4 nodes (Central Offices) with the core HL1/2 level (WAN/CDN nodes). In other words, the system enables IP-offloading of traffic onto the optical layer, saving a great amount of aggregation routers and packet processing latency and jitter.

The integrated VCSEL-based S-BVT module, enabling up to 2 Tb/s, is the fundamental element used at low hierarchical level nodes (HL4). To reduce the cost of the solution, low-cost switches are envisioned at the HL4 nodes for simple add/drop functionality, using 50 GHz arrayed waveguide gratings (AWGs). At the upper hierarchical levels (HL3 and HL2/1), the nodes are more complex and based on 100-GHz multiplexers and wavelength selective switches (WSSs) with 25 GHz granularity, to include additional functionalities for handling both the spectral and spatial dimensions [1].

An intelligent SDN-based control plane is in charge of dynamically routing and bonding an arbitrary amount m of 25, 40 and even 50 Gb/s channels, leading to a total aggregated capacity of up to multi-Tb/s.

In this context, the target is achieving valid all-optical bidirectional channels from edge MAN nodes (HL4) to core MAN nodes (HL1/2), including both link-and-node-disjoint primary and backup paths. The viability of those multi-level direct paths is given by their optical signal to noise ratio (OSNR).

Fig. 1: (a) Channel distribution in HL4 and HL3 nodes; Examples of required OSNRs for given target capacities: (b) 4 HL3-HL2/1 nodes; (c) 2 HL4 nodes.

2. Capacity evaluation in multi-hop propagation

In order to evaluate the viability of primary and backup paths in a huge MAN, we employed a simulation tool that proved to be in good agreement with the experimentation in case of single side-band (SSB) DMT DM-VCSELs in presence of tight filtering [1, 3]. The tool allows to determine the OSNR threshold required to cross a certain number of nodes of different types to achieve a capacity per VCSEL of 50 Gb/s, 40 Gb/s and 25 Gb/s, respectively, taking into account the proposed S-BVT characteristics.

In parallel, in the hypothesis of standard single mode fiber (SSMF) propagation with 0.25 dB/km attenuation and Erbium-doped fiber amplifier (EDFA) amplification with 6 dB noise figure (NF), for each MAN primary and backup path we calculated the associated OSNR budget with the linear model presented in [4]. By comparing the OSNR thresholds obtained by the simulation tool with the path OSNR budgets, it is possible to guarantee which paths, supporting one of the three target capacities, can be set up. In particular, the simulation analysis takes into account the impact of HL4, HL3, and HL2/1 node crossing for seven 25-GHz spaced WDM channels modulated with an SSB DMT signal. Each channel is generated by a 18-GHz VCSEL, which is directly modulated with a 16-GHz DMT signal with 256 subcarriers. As depicted in Fig. 1(a), in the HL4 rings the channels are 50-GHz spaced, while at the first HL3 node channels with 25-GHz spacing are added for a total of seven. After propagation in SSMF, a 25-GHz coherent receiver detects the signal. The receiver DSP provides for chromatic dispersion compensation, digital synchronization, cyclic prefix removal, subcarriers phase recovery, demodulation, and error count. Chow's bit- and power-loading algorithm is used to compute the transmitted capacity for a target BER of $3.8 \cdot 10^{-3}$ (as for 7% OH hard decision FEC).

Fig. 1 shows examples of the dependence of the required threshold OSNRs to achieve 50 Gb/s, 40 Gb/s, and 25 Gb/s capacity per channel on the number of crossed: (b) HL4 nodes and (c) HL3-HL2/1 nodes. Due to a wider bandwidth, the impact on performance of HL4 node crossing is lower than HL3 one. Indeed, in the case of HL4 crossing, we observe a slight improvement in the OSNR thresholds due to a more effective vestigial sideband filtering, by the cascading of off-centered 50-GHz flat-top AWGs. On the other hand, due to HL3 level narrow filtering the impact on transmission performance is quite high for an increasing hop number: at 50 Gb/s per channel, up to 6 HL3 nodes can be supported with a threshold OSNR of around 38 dB. A custom behaviour is represented by the case of 3 HL3 nodes for which a lower OSNR threshold is obtained with respect to the 2 HL3 case due to a better suppression of the inter-channel crosstalk from the adjacent channels. Of course, for 40 Gb/s and 25 Gb/s capacities, the OSNR thresholds are lower and more than 9 HL3 nodes can be traversed.

3. Evaluation on a large MAN topology

The topology under study comprises a large MAN featuring 419 nodes and 531 links, where nodes are organized hierarchically into three levels, namely HL4-Access (380 nodes), HL3-Aggregation (33 nodes) and HL2/1 Metro-Core (6 nodes). The average link length and node degree are 8.65 km and 2.57 links per node respectively. This topology is real, it serves more than 20 Million customers, but has been anonymized for security reasons.

On this topology, both primary and secondary (aka backup) paths are computed from every HL4 node to the closest HL2/1 node of all six, using minimum hop distance as the routing metric (not km), since the OSNR experiments of the previous section reveal that hop-count is more critical than physical distance to achieve good OSNR margins. In the case where multiple HL2/1 nodes have the same hop-count distance, the closest HL2/1 node in terms of physical km distance is chosen. This procedure generates 380 HL4-HL2/1 primary paths. For computing secondary paths, both links and nodes participating in the primary path are removed from the topology to enforce totally disjoint paths, which is possible in only 238 backup paths. Another 142 backup paths share at most 2 nodes and 1 link with the primary path since their removal results in network disconnection.

Fig. 2 shows box-and-whisker plots for both number of hops and physical distance in km of both primary (green)

Fig. 2: Boxplots of number of hops, Link distance and OSNR for primary (green) and secondary (yellow) paths.

and secondary (yellow) paths using the methodology explained above. As shown, primary paths are obviously closer to the HL2/1, both in hop-count and physical distance, than secondary paths.

As shown, primary lightpaths can take up to 8 hops (backup lightpaths even 14 hops) and nearly 150 km distance (up to 200 km for secondary lightpaths), showing that this is indeed a very large MAN topology. Concerning OSNR, Fig. 2 shows that primary paths experience higher values than the secondary paths obviously, since primary paths are closer to the destination node both in terms of hop-count and physical distance. In this large topology, absolutely all primary paths comply with the OSNR requirements for supporting 25, 40 and 50 Gb/s; these requirements are provided by the tool overviewed in the previous section. However, 6 out of 380 backup paths are not possible at 50 Gb/s according to the OSNR requirements, but still 25 Gb/s and 40 Gb/s are supported. Essentially, the OSNR simulation tool explained in the previous section applied to this topology reveals that 50G transmission flows require between 31.6 to 38.20 dB (min and max), 40G flows demand between 26.10 and 32.60 dB OSNR, and 25G flows need between 20.40 and 25.00 dB OSNR (min and max). As shown from Fig. 2 (c) all primary paths have OSNR values above 38 dB (minimum value is 38.04 dB) while secondary paths are above 36 dB (minimum value is 36.46 dB), thus meeting the 50G, 40G and 25G OSNR requirements in more than 98% of the cases (374 of 380 backup paths).

4. Conclusions

In conclusion, all-optical lightpaths traversing multiple nodes with distances up to 200 km are possible with the proposed low-cost multi-Tb/s VCSEL-based S-BVT system, thus allowing IP offloading of all intermediate MAN nodes.

Acknowledgements

This work has been supported by EU H2020 project PASSION, grant no. 780326 (<http://www.passion-project.eu/>).

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